ARMY RESEARCH LABORATORY

Flow Visualization of Steady and Transient Combustion in a 120-mm Ram Accelerator

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A technique to visualize transient and steady combustion phenomena in ram accelerators using sacrificial transparent acrylic chambers is demonstrated. This technique allows the normal operating environment of ram accelerators to be very closely approximated. Using this technique, details of the environment during the transient starting phase as the projectile enters the accelerator and the obturator is discarded are seen for the first time. In addition, steady or running combustion around the projectile after the obtrurator has been shed is captured. These flow visualizations are shown to be useful in validating computational fluid dynamics codes and in providing guidance in reducing projectile unstarts while increasing initial accelerator performance.

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1. INTRODUCTION

Gasdynamic modeling (Nusca 1993, 1994) and experimental testing are currently underway at the U.S. Army Research Laboratory (ARL) under the auspices of the Hybrid In-bore Ram (HIRAM) Acceleration program (Kruczynski 1991, 1993). The goal of the HIRAM program is to develop launchers that will economically and routinely accelerate large masses (7 kg+) to velocities exceeding 3 km/s for hypervelocity launch and terminal effects studies. In addition, as the technology progresses, the HIRAM program is evaluating its potential use for other applications such as theater missile defense and ground launch to space.

The ARL test facility consists of accelerator tubes made from retired 120-mm, M256 tank guns, machined and mated. A solid propellant preaccelerator is used to bring the projectile up to the velocity required for ram/scram propulsion. A vent section serves the dual purpose of decoupling the conventional launch gun recoil from the accelerator (sliding interface) and venting the back pressure from the conventional charge combustion. The HIRAM facility was initially designed to accommodate five 4.7-m-long accelerator tubes for a total combined length of 23.5 m. Expansion to 60 m is possible. Gases are supplied from a bottle farm and diaphragm compressor capable of supplying five different gases at pressures up to 341 atm. A large vacuum pump installed near the accelerator is capable of evacuating any part of the launch/vent/accelerator assembly.

Instrumentation within the accelerator tube includes wall-mounted quartz pressure transducers and photo diode gages. High-speed movie and still-frame (smear) cameras are employed at various locations around the accelerator. Doppler radar is used to measure projectile exit and in-bore velocity. Gas samples are analyzed online by a portable gas chromatography system or are taken just before firing for later analysis. The current projectile is made of high-strength aluminum alloy and is geometrically modeled after designs tested at the University of Washington (Hertzberg, Bruckner, and Bogdanoff 1988; Higgins, Knowlen, and Bruckner 1993; Hinkey, Burnham, and Bruckner 1993).

Photographs of the HIRAM facility and projectile can be viewed in Figure 1. Additional details about the HIRAM facility are available in Kruczynski (1991).

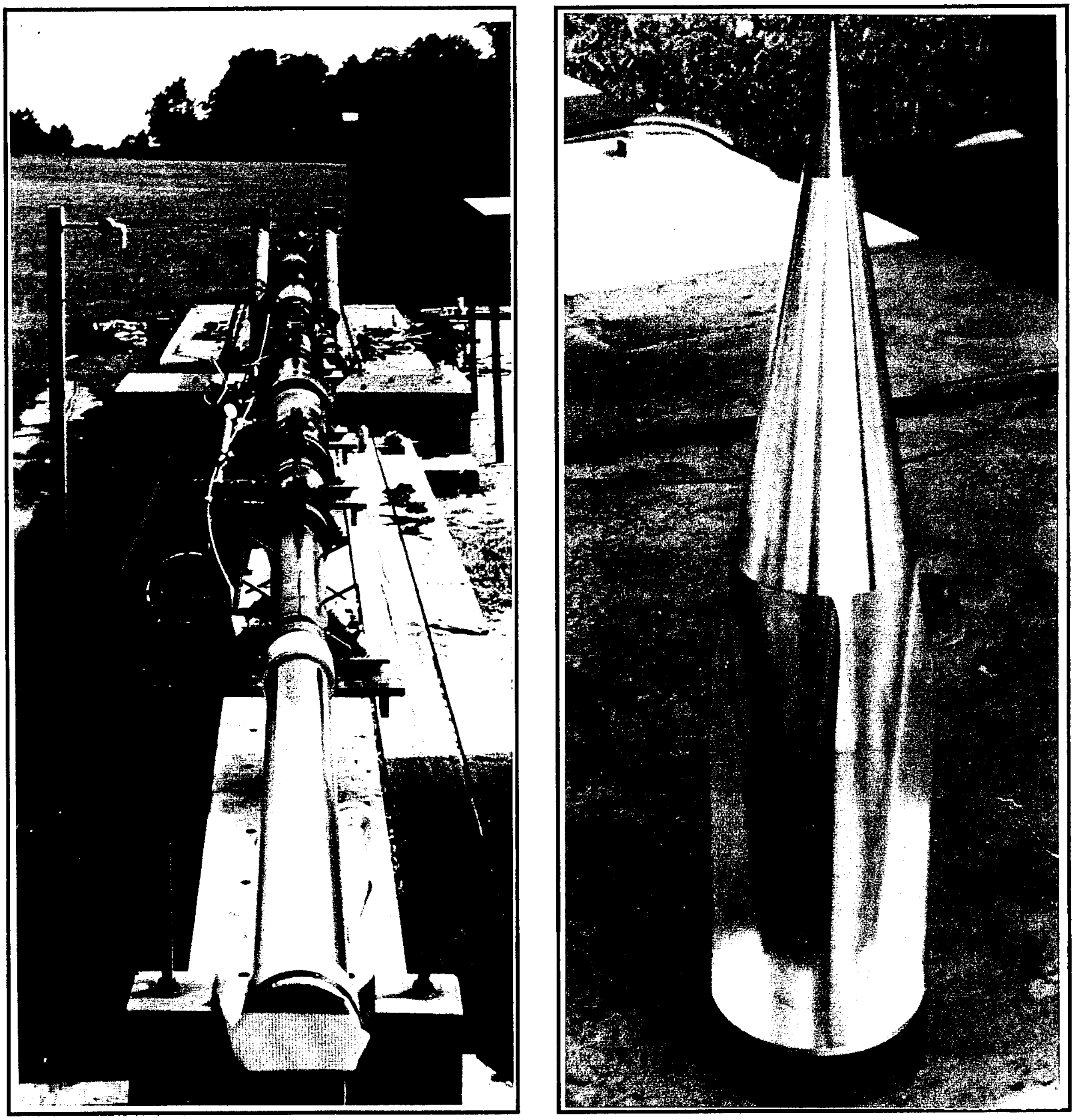

Figure 1. Accelerator with transparent chamber and HIRAM projectile. In the left photo, from rear to front, are 5.3-m-long, 120-mm-bore diameter tank gun preaccelerator, 2.1-m-long vent section and two 4.7-m-long accelerator sections. Also shown attached to end of accelerator is transparent visualization chamber. Shown in right is 0.522-m-long aluminum projectile with preaccelerator gun obturator, total launch mass is 4.80 kg.

2. MOTIVATION

2.1 Starting the Ram Accelerator. For ignition and inlet (throat) starting, the ram acceleration process currently requires the projectile be injected into the accelerator's fuel/oxidizer/diluent mixture (or simply propellant) at a velocity well above the sound speed of the mixture to properly swallow and ignite the relatively high-speed flow. In this starting regime, the physics are complex and vary with accelerator design.

In smooth-bore accelerators, projectiles ride on fins to ensure in-bore stability while allowing sufficient flow through the projectile throat. This design necessitates the use of an obturator behind the projectile during launch from the preaccelerator into the accelerator proper. The obturator serves to seal the preaccelerator gases behind the projectile for efficient acceleration and to prevent excessive leakage of gases in front of the projectile prior to entrance to the accelerator. Excessive buildup of gases in front of the projectile is capable of bursting diaphragms at the accelerator entrance well ahead of the oncoming projectile. Under these conditions, it is unlikely that the projectile throat will swallow the compressed flow preceding it, resulting in an unstart, or perhaps more appropriately, a nonstart.

While the obturator serves its necessary role in the preaccelerator, its function in the ram acceleration process is less clear. It has been assumed that the stagnation of flow on the obturator serves to ignite the accelerator propellant gases, which, once ignited, remain so during acceleration of the projectile. Early experiments at the University of Washington indicated that the flow could not be ignited without the stagnation caused by the presence of an obturator (Bruckner et al. 1991).

However, this requirement may be strongly influenced by the geometry of the accelerator and projectile, as well as the energy in the gaseous propellant and the relative Mach number of the projectile at injection. Recent successful experiments at the Institute of Saint Louis, France, with a 30-mm ram accelerator utilizing a railed tube (finless projectile) and a preaccelerator which requires no obturator (since the projectile fills the full-bore diameter), support this assumption (Seiler 1994).

Under some conditions, the obturator can both ignite the flow and provoke an unstart. This will occur, for instance, if the obturator is too massive or the back pressure from the preaccelerator is too high to allow rapid separation from the projectile base. The stagnated combusting flow and/or a normal shock will eventually disgorge through the projectile throat. Avoiding this situation requires that a complex and somewhat cumbersome venting arrangement be made that reduces the back pressure on the obturator allowing it to separate in sufficient time for stabilized flow to remain supersonic over the projectile throat. In addition, the effect of perforating diaphragms during entrance to the accelerator on projectile integrity and the starting process is largely unknown.

To date, all unstarts that have resulted during testing at ARL have occurred within the first few projectile lengths of travel in the accelerator. While limited testing with online gas chromatography indicates that some unstarts may be explained by incomplete mixing of the propellant gases, which can result in localized high-energy regions in the flow, there is sufficient mystery in the starting process to support this study. There is also a companion computational fluid dynamics (CFD) study (Nusca 1994) to enhance the understanding of the process occurring during the critical starting phase in ram accelerators. It was felt that a better understanding of the transient starting process would assist in reducing the need for complex venting arrangements while eliminating or greatly reducing the chances for initial unstarts.

2.2 Running Combustion in a Ram Accelerator. Once ignition of the propellant gases has occurred and the obturator is separated sufficiently from the projectile base (several projectile lengths), the projectile can be said to be cruising, or running, with stabilized combustion, controlled by the strength of the shock system over the projectile and the energy of the propellant gases. In this mode, the projectile will continue to accelerate until either the energy release ahead of the projectile throat exceeds that released behind the throat, or the heat release behind the throat is sufficient to produce pressures that choke the flow and disgorge combustion/shocks through the throat. The latter failure mode is a classical unstart seen in scramjet engines. The former failure mode is unique to ram accelerators and is attributed to the premixed propellant mixture through which the vehicle accelerates.

Projectile structural failure will also provoke an unstart. Projectile failure can be attributed to heat-induced structural weakening, unbalanced or localized pressures loads, or ablation. When an unstart occurs the projectile is almost always found to be destroyed. However, it has not been possible to discern if the unstart was caused by the projectile failure or if projectile failure is a result of the unstart. It was, therefore, desirous to develop a technique to view these processes in as near to the normal operating environment as possible to assist in analysis of the physics involved and confirm CFD efforts.

3. EXPERIMENTAL DESIGN

3.1 Starting Visualizations. Experimentally visualizing the starting process proved to be more challenging than visualizing running or steady combustion. This was largely due to the violent combustion/venting from the preaccelerator, which is not present further along in the accelerator. In addition, should the projectile burst through the chamber walls at the beginning of the accelerator, the remainder of the accelerator and nearby instrumentation could be damaged. Further, it was desirous to capture the entire sequence at start, including activity at the entrance diaphragm, which necessitated a more complex experimental arrangement. For these reasons, the steady combustion visualizations were performed before the transient/starting visualizations. However, for clarity, they continue to be reported in the order in which the processes occur in the ram accelerator.

The experimental setup used in the transient visualizations is shown in Figure 2. The primary components in the system are transparent acrylic tubes with nominal internal diameters of 120.7 mm and external diameters of 146.1 mm. Since the ARL projectile's maximum diameter is 119.8 mm at the fins, these tubes very closely mimicked the interface dimensions between the actual steel-accelerator tubes (120-mm diameter) and the projectile. The first tube (from the left in Figure 2) is nominally 0.91 m in length and is attached to the vent section and evacuated to about 0.05 atm prior to firing. This evacuated tube is attached to a flange that mates to a 1.83-m-long acrylic tube. The flange also incorporates a diaphragm that can be of any desired material. The second tube is sealed at its free end by a second diaphragm and retaining cap, which is further enclosed in a retaining box bolted to the accelerator-mounting I-beam. This second tube was filled with the desired propellant. While steady combustion visualization tests at pressures in excess of 50 atm have been conducted, the acrylic tubes used for these studies were inconsistent in mechanical properties beyond 20 atm. In addition, there was concern for exposed instrumentation in the relatively violent combustion of starting. It was therefore decided to limit the propellant pressures in the starting study to 20 atm.

The entire preaccelerator (gun and vent) is intentionally obscured from view by large shields, as seen in Figure 2. The function of these shields is to block the highly luminous gases from the preaccelerator from overwhelming the processes being filmed in the transparent chambers.

Instrumentation employed in these studies included three 16-mm, high-speed (5,000–10,000 frames per second [f/s]) color cameras focusing on various locations in the transparent tubes. A 35-mm, black-

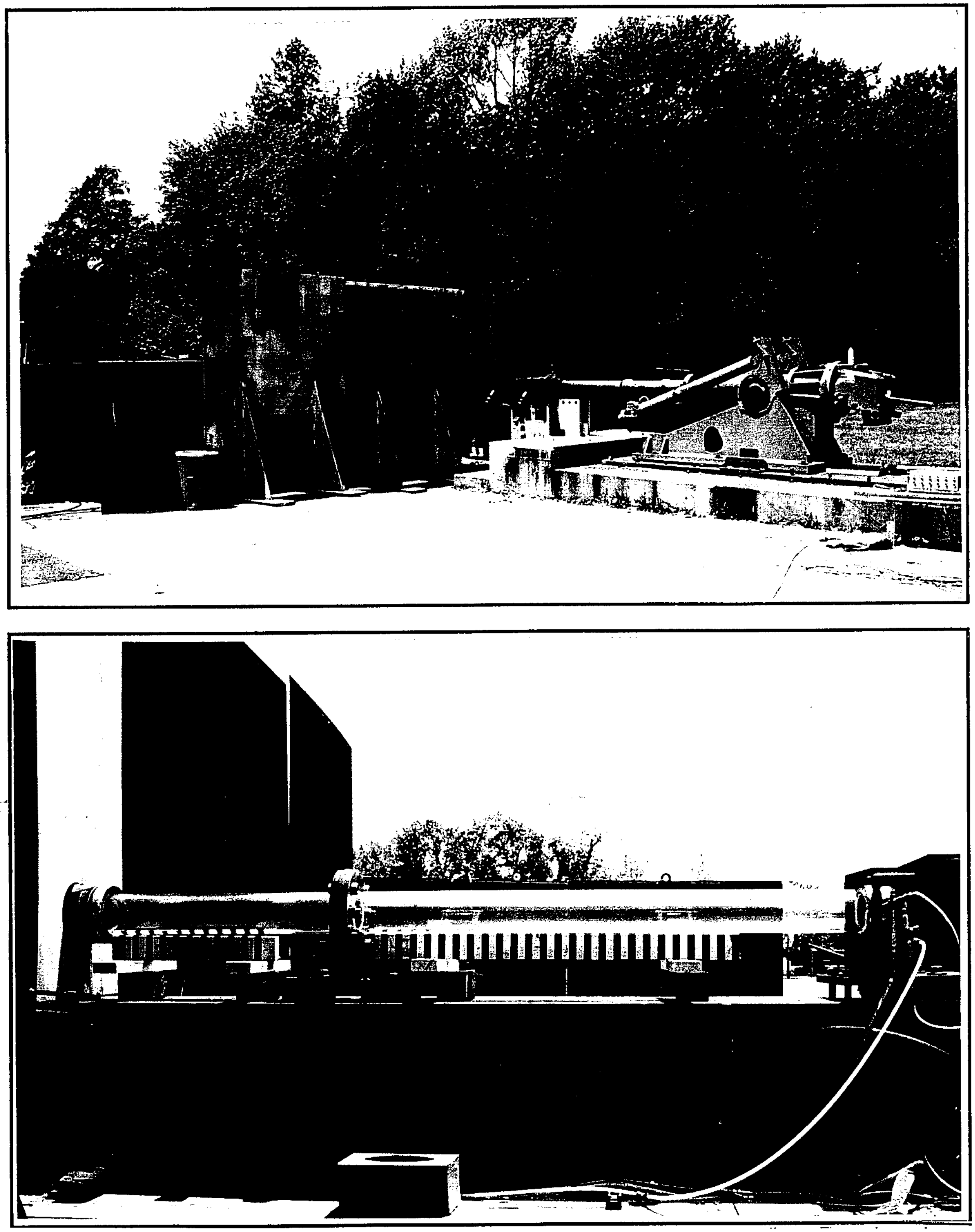

Figure 2. Two views of experimental setup for transient (starting) combustion studies. Top view shows preaccelerator and vent section which are blocked from view of the transparent sections to reduce the excessive light from the venting process. Bottom view, from left to right, shows 0.91-m-long transparent tube attached to the vent, flange with diaphragm, and 1.83-m-long transparent tube filled with the fuel/oxidizer.

and-white smear camera was focused near the end of the second tube to capture a still image of the projectile intube. In addition, a standard VCR camera recorded the firings. Radars of 10 and 15 Ghz were reflected into the tubes to measure intube velocity profiles. In addition, a scale that ran the length of the transparent tubes was used for direct measurement of projectile/obturator travel through film analysis.

No steel-accelerator tubes were employed beyond the sacrificial acrylic tubes due to the potential for damage. The fuel/oxidizer diluent used was (on a molar basis) $2O_2 + 10\ N_2 + 3\ CH_4$ at 20 atm. The dimensionless heat-release values ($\Delta Q/C_pT$), sound speed, and Chapman-Jouget detonation velocity for this mixture at this pressure are 3.0, 361 m/s, and 1,442 m/s, respectively. After the first test (shot 30), changes were made to the standard obturator and projectile to promote visualization (Figure 3).

3.2 Running Visualizations. To visualize established or running combustion, a 1.83-m-long acrylic tube of 127-mm i.d. and 152-mm o.d. was used. It was attached to the end of a 9.4-m-long accelerator. There was no diaphragm at the accelerator/acrylic tube interface (O-ring seal) allowing unimpeded transition from the standard steel-accelerator tube into the transparent section. It was sealed at the downrange end with an aluminum cap and PVC diaphragms. It was pressurized along with the steel-accelerator tube to 51 atm with the same mixture described previously for the starting tests. The dimensionless heat-release values ($\Delta Q/C_pT$), sound speed, and Chapman-Jouget detonation velocity for this mixture at this pressure are 3.3, 361 m/s, and 1,466 m/s, respectively. The test setup is depicted in Figure 4.

4. RESULTS

4.1 Starting Visualizations. The first shot in the series (shot 30) showed that, as long suspected, the obturator does not provide a perfect seal of preaccelerator gun gases up to accelerator entrance. A significant amount of light from preaccelerator gases was seen to lead the projectile into the first transparent tube. These gases led the projectile by over a half a meter and piled up against the entrance diaphragm, totally obscuring the projectile on entrance. These gases did not burst the diaphragm and the projectile caught up with and passed them during diaphragm puncture. The obturator was seen to be off the projectile base and cocked as the projectile entered the second transparent section.

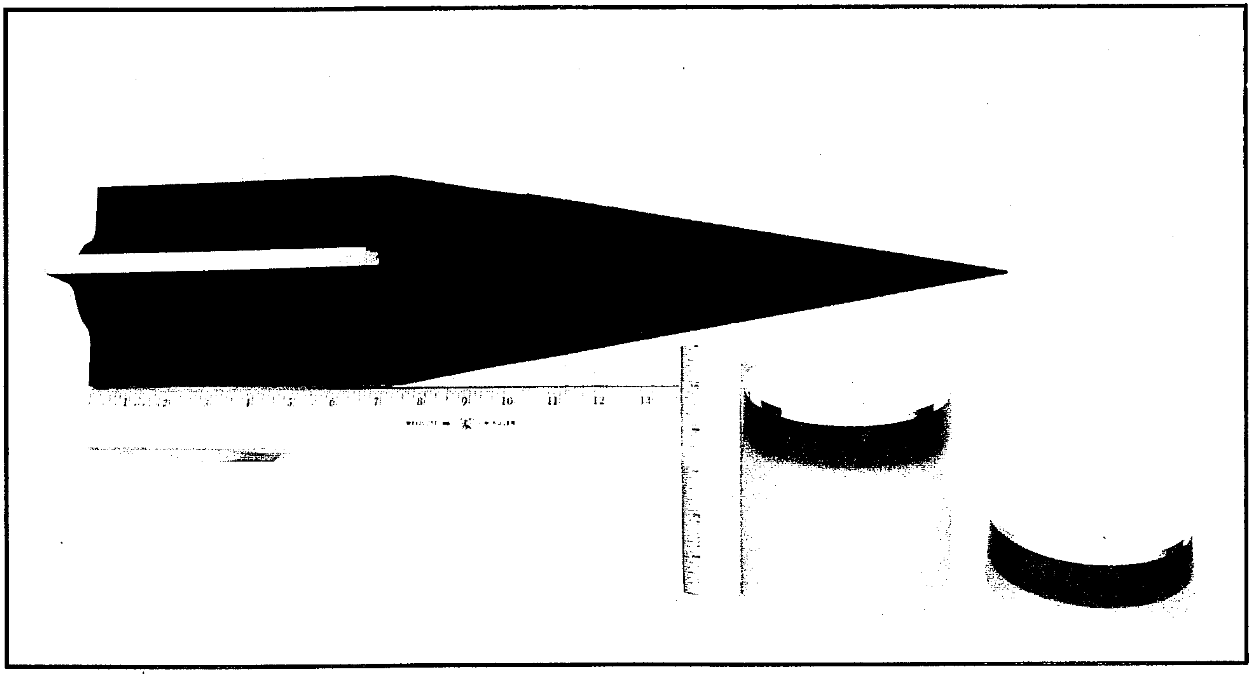

Figure 3. Photos show enhancements made to the projectile and obturator to lessen light leakage past the obturator (blowby) and improve visualization of the projectile in the transparent chamber. Obturator length was increased to preclude in-bore cocking and projectile was painted black with temperature resistant paint.

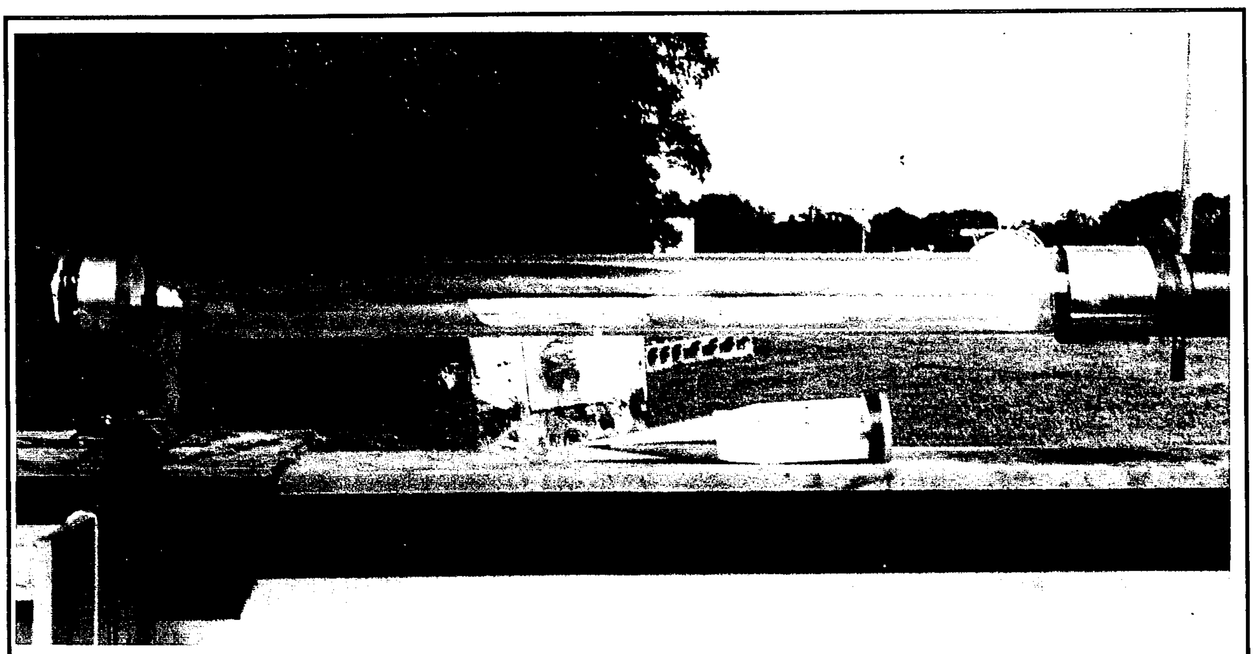

Figure 4. Photo showing 1.83-m-long transparent chamber attached to the end of the accelerator for steady (running) combustion visualization. The projectile is shown under the chamber for comparison.

The projectile in shot 30 did start and accelerate through the second chamber; however, the gaseous blowby, light from ram ignition, and reflective aluminum projectile combined to prevent significant details of the process to be clearly seen. For the next test (shot 31), the obturator was lengthened considerably to both promote better sealing and prevent in-bore cocking. In addition, the projectile was painted flat black with a temperature-resistant paint. These changes can be seen in Figure 3.

Shot 31 revealed reduced but still significant light leakage by the obturator during entrance into the first evacuated transparent section. However, a combination of the reduced light, the blackened projectile, and improved camera angles were able to reveal significant details of the combustion process.

Shown in Figure 5 is a series of frames from a high-speed movie camera running at 7,000 f/s and aimed at a 30° angle towards the oncoming projectile (traveling right to left). In the first frame of Figure 5, the mylar diaphragm at the entrance to the second clear chamber can be seen backlit by the preaccelerator gasses that have entered the first evacuated test section ahead of the projectile and are building up on the diaphragm face (see Figure 2 for location reference). In the second frame, the projectile nose is clearly seen piercing the diaphragm and has entered the second visualization chamber about 127 mm, or a quarter of a projectile length. In the third frame, the projectile has entered to approximately 254 mm, or to the throat of the projectile. Note that no combustion in the second chamber has occurred up to this point. In the next frame (not shown), intense combustion masks the projectile. This is better seen in Figure 6a.

Figure 6a is a side view of part of the entrance section (evacuated) and the first two-thirds of the combustion visualization chamber. The camera is running at 9,000 f/s. In the first frame, the projectile is just entering the combustion chamber (traveling left to right). In frames 2 and 3, intense combustion activity masks the projectile. By frame 4, the projectile can be seen outrunning the intense combustion with about two-thirds of the projectile nose clear of combustion activity.

Figure 6b is a continuation of the movie strip in Figure 6a. In the first two frames, the nose of the projectile stays just ahead of the intense combustion. In the last two frames, the combustion intensity begins to lessen and to take on a more flame-like structure similar to that seen in running combustion.

Figure 7 is a black and white smear (still) camera shot of the projectile just before exit from the combustion chamber (1.8 m of travel in combustible mixture). At this point, most of the nose is visibly

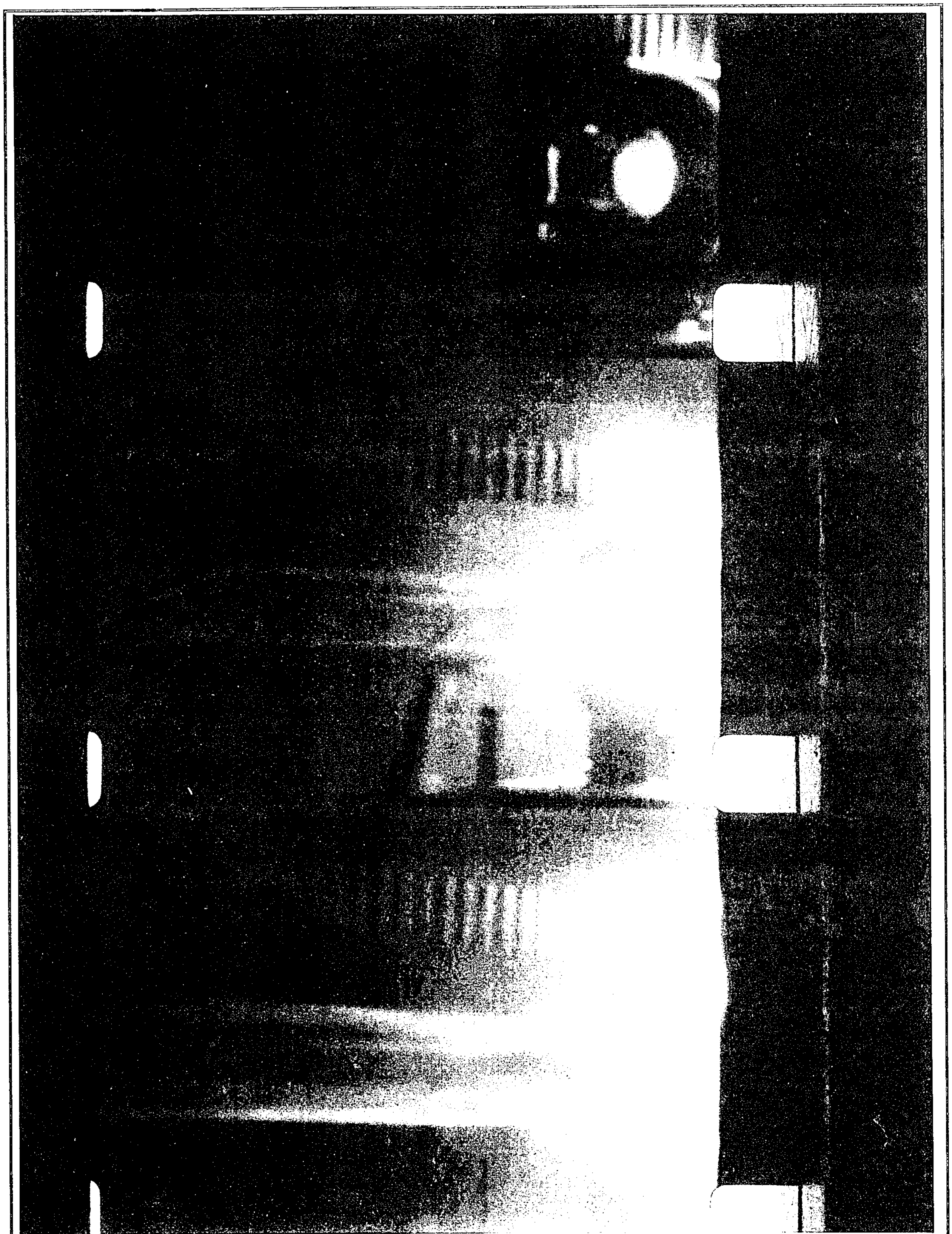

Figure 5. Frames from high-speed movie of shot 31 penetrating the mylar diaphragm and entering the second transparent tube. The diaphragm is backlit by light from combustion in the preaccelerator. In the second and third frames, the projectile pierces the diaphragm and enters the clear chamber.

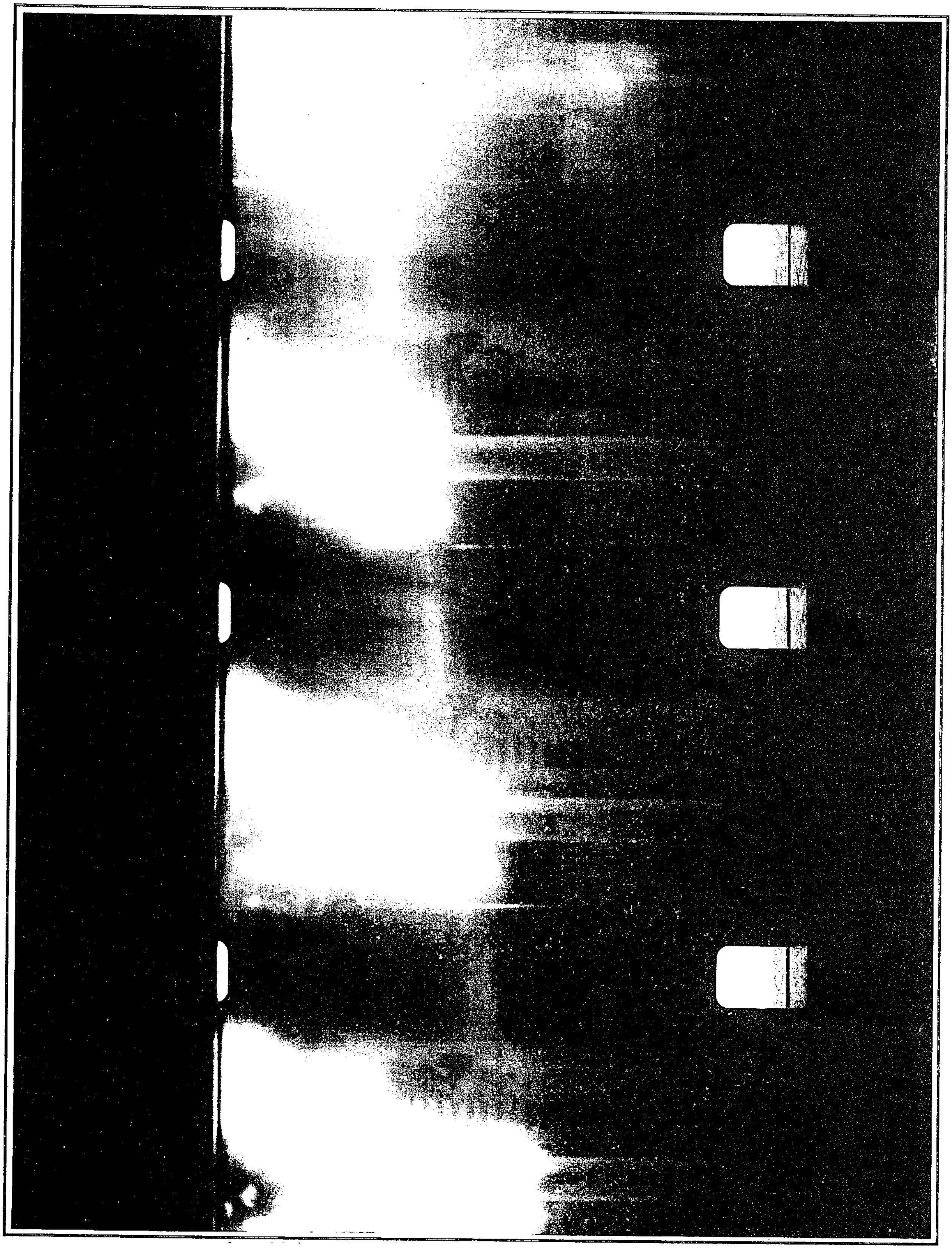

Figure 6a. Frames from high-speed movie of shot 31 entering the combustion chamber and startup of ram combustion. Very intense light in first few frames indicate critical time when the obturator is close to the projectile's base.

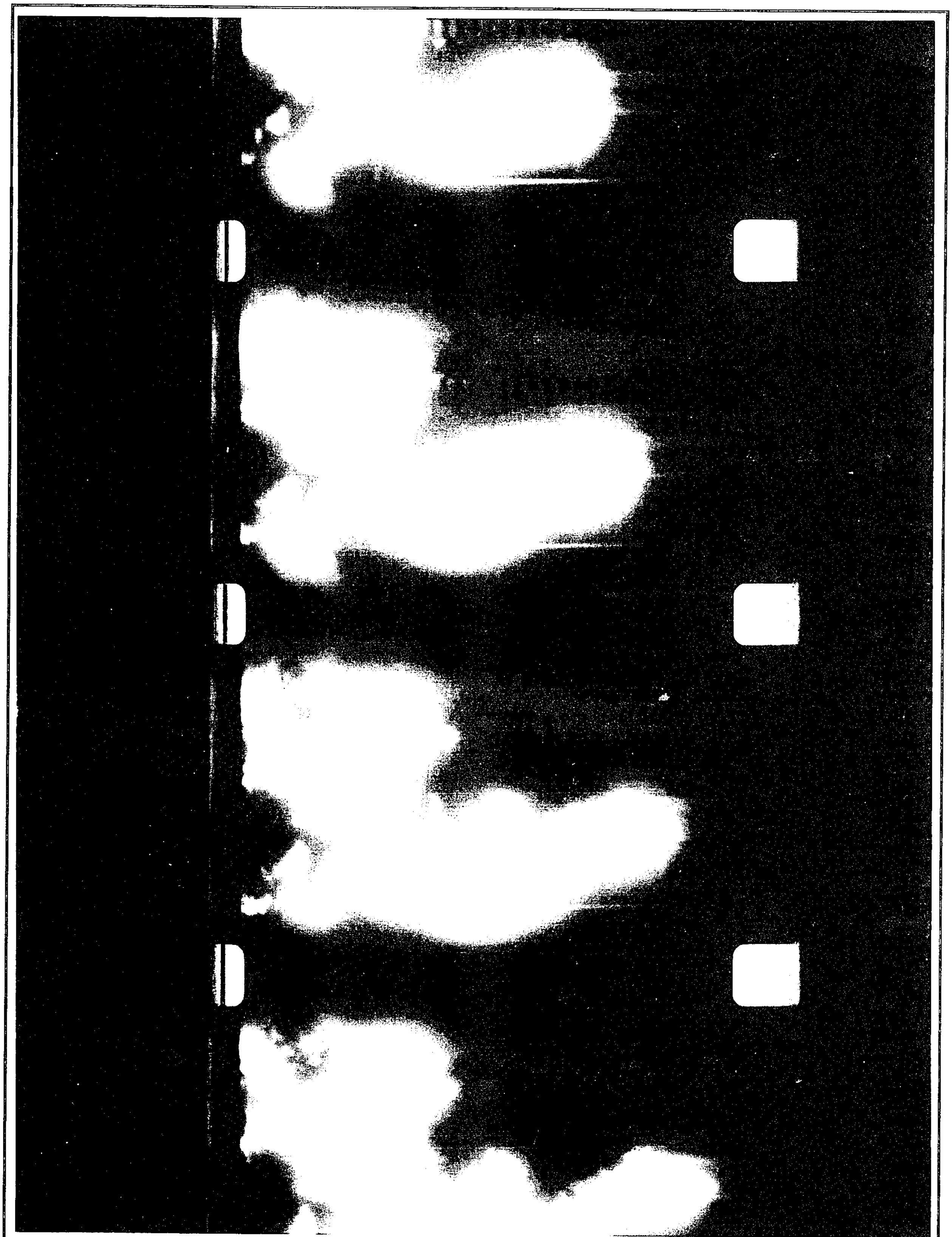

Figure 6b. Frames from high-speed movie of shot 31 entering the combustion chamber and startup of ram combustion. The projectile is moving away from the obturator while the combustion is moving back on the projectile body.

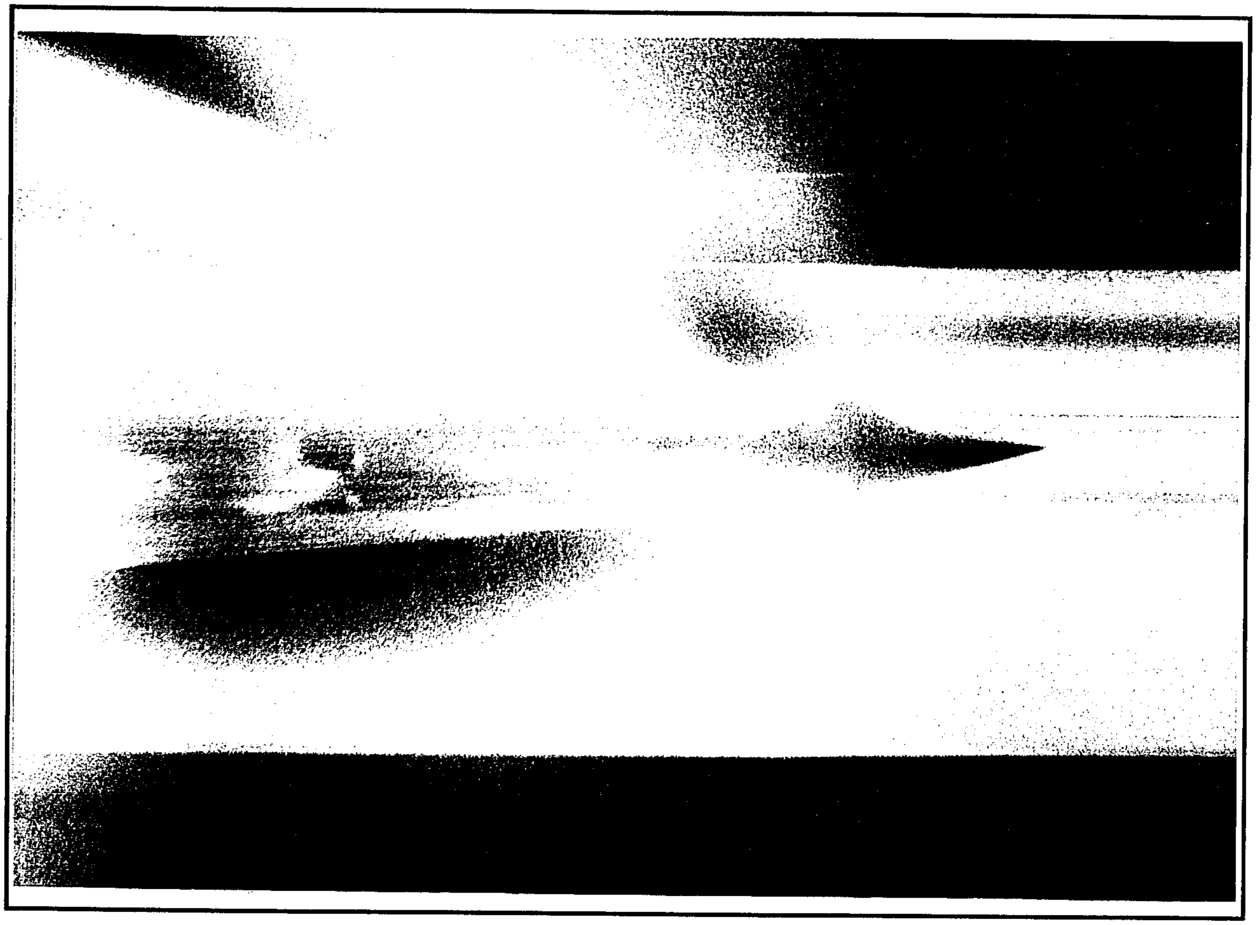

Figure 7. Smear (still) photograph of projectile in-bore nearing the end of the transparent chamber. Combustion masks the rear of the projectile body. The obturator can be seen 1 1/4 of a projectile length (0.653 m) behind the projectile's throat.

combustion free while the aft end of the projectile is immersed in combustion. The obturator is seen trailing the projectile by about 360 mm, or about two-thirds of a projectile length. Note that the obturator appears to be broken up somewhat, allowing some flow to pass through it. Note also that the projectile nose tip appears to suffer no damage from diaphragm puncture and there is no indication of combustion in the nose region. The projectile velocity and Mach number at this point are 1,300 m/s and 3.6, respectively.

4.2 Running Visualizations. Figure 8 is a side view of a projectile (shot 27) accelerating through the running visualization section (traveling right to left) shown in Figure 4. The sequence of frames is from a high-speed movie running at 5,000 f/s. Note that this section is attached at the end of a second accelerator tube and is located 9.4 m from the entrance to the accelerator. Since the obturator is well downstream of the projectile, at this point, the combustion profile through this section is relatively constant with the primary combustion zone located near the throat (and fin leading edges). The transparent tube

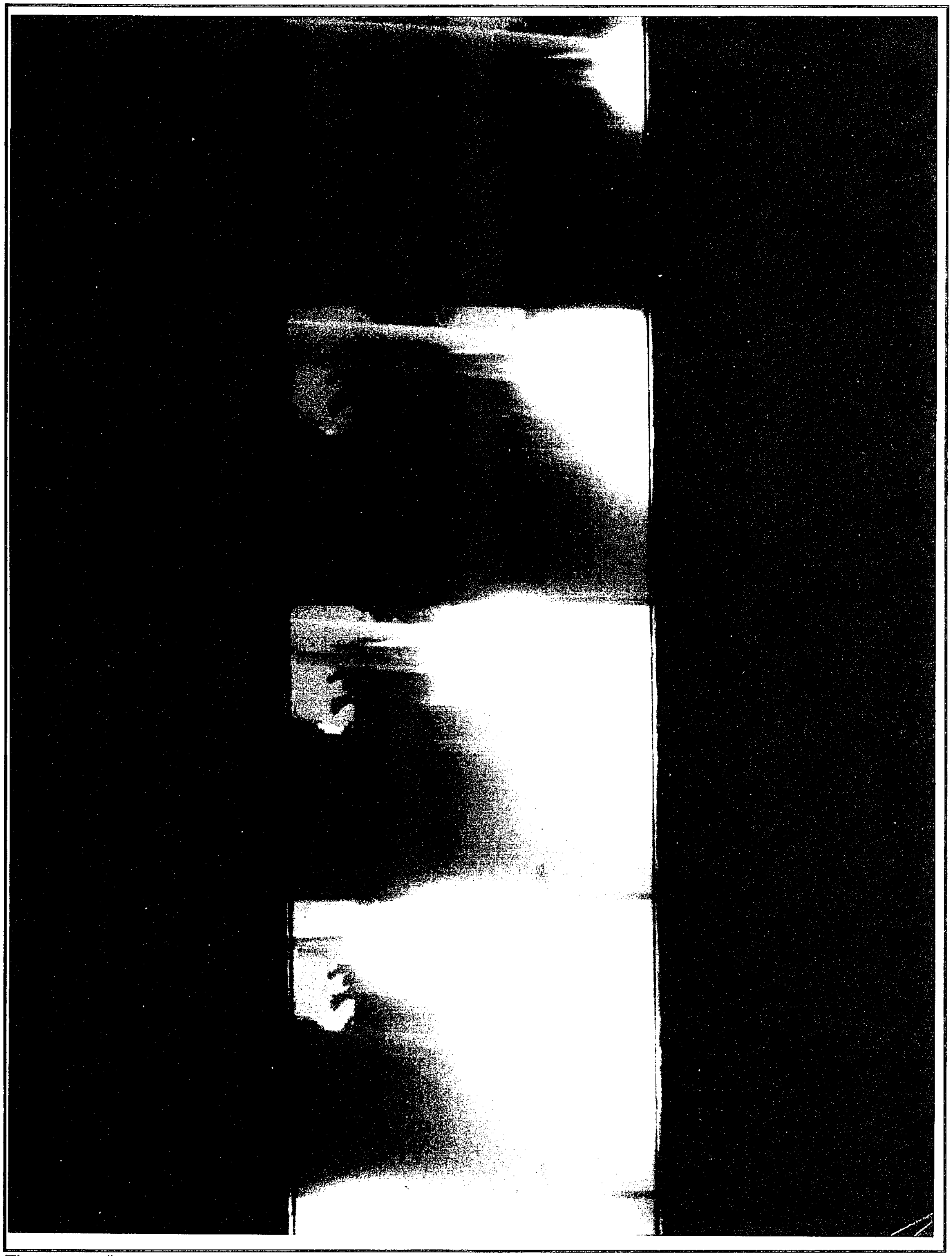

Figure 8. Frames from high-speed movie of shot 27 as the projectile accelerates through the transparent chamber with ram combustion established.

used in this test is slightly oversize (127 mm), leaving 7-mm-diametric clearance around the fins. This clearance appears to allow the projectile to cock slightly in-bore. The combustion around the projectile does not appear to be greatly effected by the projectile nonsymmetry. The peak projectile velocity and Mach number in this section are 1,480 m/s and 4.1, respectively.

5. ANALYSIS

The starting process appears to exhibit several tendencies predicted by CFD calculations (Nusca 1994). As the projectile enters the optically clear combustion chamber with the obturator closely behind it, the incoming flow stagnates on the obturator face and bulk ignites the flow from the obturator forward over at least two-thirds of the projectile. This combustion is very intense as evidenced by extreme light emission.

As the projectile accelerates away from the obturator, the combustion moves back on the projectile body and becomes much less intense. The combustion, which now stabilizes near the throat region, also appears to develop evidence of some flame structure. In a case such as shot 27 where the obturator is very far downstream from the projectile base (many projectile lengths), the combustion appears stabilized with combustion located in the throat/fin leading edge region.

In the current visualizations, the shock structure around the projectile, especially in the combusting regions, was not visible. However, time-accurate CFD simulations of the startup and stabilization of combustion including sabot discard under similar conditions (but higher pressure—50 atm) reveal that a normalized shock starts in the stagnated flow near the base of the obturator and moves forward during the early motion of the projectile. This shock very nearly disgorges through the throat before moving backwards as the obturator is shed, relieving the backpresure behind the projectile (see Nusca [1994] for further details).

Although the visualization experiments were by necessity conducted at lower pressures (20 atm) than the CFD simulations, the same trends in flow conditions are believed to be accurate. For instance, the lower pressures of the experiments would slow obturation separation, however, this effect on the combustion environment would be partially offset by slower propellant kinetics.

The combination of combustion on and the normal shock nearing the projectile forebody provides a precarious situation in terms of the possibility for a projectile unstart. Slight perturbations in mixture chemistry, obturator integrity, and/or projectile stability could quickly invoke an unstart.

To reduce the probability of an unstart, it appears desirable to capture or modify the obturator such that ignition onset and intensity is controlled and repeatable. Conceivably, a higher degree of confidence in initial combustion conditions would also allow higher energy propellant mixtures to be used with lower probability of initial unstarts.

6. CONCLUSIONS

- Flow visualization techniques for transient and steady combustion in normal or near normal conditions have been demonstrated.

- Transient flow visualizations indicate that very intense combustion is exhibited around almost the entire projectile body until the obturator is well downstream of the projectile. This confirms CFD calculations for these conditions.

- Steady flow visualizations reveal stable combustion from the projectile throat back after the obturator is shed.

- Reductions in unstarts and potential performance increases are suggested by the abatement in the severity of initial combustion using improved control of the obturator location relative to the projectile.

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